Report as of FY2010 for 2010IN219B: "Local and Regional Assessment of Biofuel Production Facilities Impacts on Freshwater Quality in Indiana"

Publications

Project 2010IN219B has resulted in no reported publications as of FY2010.

Report Follows

Local and Regional Impacts of Biofuel Production Facilities on Freshwater Quantity and Quality in Indiana

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IWRRC 2010 Project Report

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Abstract / Summary
Freshwater plays a crucial role in all stages of biofuel production - from biomass cultivation through its conversion into biofuel. Corn ethanol production increases may further compromise water quality and compete with other sectors of freshwater use (e.g., urban and industrial). The effects of expanded biofuel production on freshwater, a limited but a renewable natural resource, need to be considered as demand for freshwater from various sectors increases and places additional stress on already constrained freshwater supplies. An increase in corn cultivation using current intensive agricultural practices will also impair water quality as a result of the runoff of fertilizer and pesticides into surface water and groundwater. Moreover, biorefineries also discharge wastewater containing several inorganic and organic contaminants that could impair surface-water quality and compound the problem on already impaired freshwater. Therefore, both quantity and quality of freshwater should be considered when assessing the impacts of biofuels production expansion on local and regional freshwater. The water use regime, originally proposed by Weiskel et al. (2007), is adopted for this research and modified to take into account water quality impacts by non-point sources in addition to quantity on the degree of human influence on region's hydrology. The *criticality ratio* is also combined as a method of determining water stress. Eight watersheds (HUC-8), within which biorefineries are currently in operation and are located within the band of mid-northern part of Indiana, were selected for an evaluation of shifts in "water-use regimes". Our analysis shows that, at the *watershed scale,* the consumptive water uses from various major sectors are small under average weather conditions. This evaluation, however, changes dramatically when *water-quality impairments* are taken into account; all watersheds we evaluated would be judged to be under severe water stress. Moreover, under *drought conditions*, all watersheds we examined would be judged to be under severe stress both from quantity and quality perspectives. Competing demands for freshwater are most likely to be experienced at spatial scales smaller than a watershed scale. This is especially important since freshwater withdrawals are from groundwater sources, but return flows are to surface water (streams). Thus, continued depletion by increasing pumping from aquifers can, over time, result in significant water stress conditions. Freshwater use data we utilized in our analysis came from the USGS reports which are published once every five years, and are available aggregated only at the county level. We did not access data that might be available with the local authorities who issue permits for groundwater use. Our assessments would be enhanced if such local-scale data were used to generate the water regime plots, and these plots would be even more useful to local water managers. Hydro-climatic shifts projected climate change [increased frequency of extreme events] would increase the likelihood of water-stress in the watersheds.

Statement of Critical Regional/State Freshwater Problem

The annual bioethanol production capacity in the United States has increased rapidly and reached 55 billion liters as of January 2009. Indiana, a major contributor to this trend, is the sixth highest bioethanol producing state (RFA 2010). Water plays a crucial role in all stages of biofuel production - from cultivation of feedstock through its conversion into biofuel (Aden 2007). The National Research Council (Hill et al. 2006) and other studies (Donner and Kucharik 2008) have warned that the corn ethanol production increases may further compromise water quality and compete with other sectors of water use (e.g., urban and industrial).

Freshwater is a limited, but a renewable natural resource, and many parts of the world or even the United States are already experiencing water scarcities. These scarcities are complicated by increasing demands of a growing population and economies. Moreover, as demand for water from various sectors increases and places additional stress on already constrained freshwater supplies, the effects of expanded biofuel production may need to be considered (GAO 2009). Although, total surface water withdrawals for Indiana did not show significant increasing trend over time, relatively large annual fluctuations have occurred (Indiana State 2008). Moreover, it is important to take into account the local or regional variability of water availability and also current and projected use trends. According to GAO’s 2003 survey, Indiana was among the states which, under average water conditions, that are likely to experience water shortages in one or more localized areas within 10 years from the surveyed year (GAO 2003). Some communities have become concerned that freshwater withdrawals for biofuels production would have adverse impacts on their drinking water and municipal supplies, and are pressuring states to limit water use by bioethanol facilities. For example, at least one Minnesota local water district denied a permit for a proposed biorefinery based on concerns about limited water supply in the area (GAO 2009).

An increase in corn cultivation using current agricultural practices will also impair water quality as a result of the runoff of fertilizer and pesticides into surface water and groundwater, leading to impacts at the scales of the entire Mississippi River Basin and the Gulf of Mexico (e.g., Donner et al. (2004) and Donner and Kucharik (2008)). Fertilizer runoff can lead to nutrient enrichment, harmful algal blooms, decreased water clarity, and anoxia in the water, all of which impair aquatic habitats. The application rates of atrazine, a commonly used herbicide for corn production, are highest in the Corn Belt, and it was also the most widely detected pesticide in watersheds in this area (Capel and Larson 2001). Moreover, biorefineries also discharge wastewater containing several inorganic and organic contaminants that could impair surface water quality (Schnoor et al. 2008). However, the type of contaminants discharged varies by the type of biofuels produced and the biomass conversion technology used. For example, ethanol biorefineries generally discharge chemicals or salts that build up in cooling towers and boilers or are produced as waste by reverse osmosis, a process used to remove salts and other contaminants from water prior to discharge from the biorefinery. In contrast, biodiesel refineries discharge other pollutants such as glycerin that may be harmful to water quality (GAO 2009).

According to Indiana Department of Environmental Management (IDEM), Indiana’s water bodies have already been highly impaired in terms of organic compounds (rank 1 among U.S. states) and biological community (rank 7), and that this situation is likely to only increase (Indiana State 2010). Although, there is multitude of sources for freshwater contamination, the increase of biofuels production will compound the problem because biorefineries produce wastewater with high concentration of organic and inorganic constituents and they require high amount of freshwater use. New source of freshwater (most likely, groundwater) is required to treat or dilute the contaminated effluents from biofuels production process. Therefore, both quantity and quality of freshwater should be considered when assessing the impacts of biofuels production expansion on local and regional freshwater.

Related Research

There have been several efforts to estimate water use for biofuel production. Gerbens-Leenes et al. (2009) estimated the water footprint (WF) of bioenergy from 12 crops that currently contribute the most to global agriculture production. Although, they had calculated the WF of each crop by country and bioenergy to be produced, this study is focused only on the agricultural (biomass) production stage. To overcome the limitations of prior studies, which had not accounted for the varied regional irrigation practices on estimating the water requirement for bio-ethanol production, Chiu et al. (2009) used regional time-series data for agricultural and ethanol production in the U.S. to estimate state-level field-to-pump water requirement of bioethanol across the nation. They estimated the embodied water in ethanol by state and evaluated the local impacts in terms of groundwater withdrawal caused by bio-ethanol production; however, they only considered the corn ethanol industry even when projecting the expansion of the biofuels industry.

Data Analysis & Technical Approach

Since most of the studies have been done at a large scale, global or national, and are highly focused on feedstock growth, this study aims to investigate local and regional impacts of freshwater use and wastewater discharges, especially from biofuel conversion processes. Indiana, in USDA farming Region 5, does not use much irrigation water for feedstock cultivation compared to other Regions, which means changing or increasing feedstocks production will not have much impact on freshwater withdrawals. Therefore, freshwater uses in biorefineries for biomass conversion will have relatively high potential to introduce local- or regional-scale conflicts for competing uses and quality impairment. Thus, water required for biomass conversion facilities will especially be highlighted in this research. While freshwater uses for biofuels conversion processes have local impacts on water problems, the discharge of wastewater effluents from those facilities have potential to expand the scale of the problem to region or interstate levels. However, wastewater quality from biorefineries has not been investigated.

The methods used to determine the appropriateness of bioethanol plant locations in Indiana follow those outlined by Weiskel et al. (2007). The method is briefly explained below, and the reader is referred to Weiskel et al. (2007) for more detailed explanation. In this study, a water-use regime is created for each watershed containing a bioethanol plant. The water use regime is defined by considering the water balance of a bounded watershed.

$$P + (GW_{in} + SW_{in}) + H_{in} - \Delta S/\Delta t = ET + (GW_{out} + SW_{out}) + H_{out} \qquad (1)$$

where P is precipitation; $(GW_{in} + SW_{in})$ is groundwater and surface water inflows; ET is evapotranspiration; $GW_{out} + SW_{out}$ is groundwater and surface water outflows; H_{in} is total return flow to the control volume from all sources, including return flows from local withdrawals and imported withdrawals; H_{out} is withdrawals from the control volume; and $\Delta S/\Delta t$ is the rate of change in control volume storage (surface and subsurface). All units are volume/time (L^3/T).

Although, Weiskel et al. (2007) recommended consideration of stream basins and aquifers separately, it is assumed here that the change of net storage in aquifer is negligible when averaged over the period of interest, which implies $GW_{in} \approx GW_{out}$. Thus, overall water balance is mainly determined by the change of surface water flow. This assumption is feasible because, in Indiana, most of the water demand in agricultural sector, which generally is the major source for local freshwater demand, is known to be fulfilled by rainfall and the irrigation rate from groundwater is relatively low (Wu et al. 2009). Therefore, only the water balance for stream basin is explicitly evaluated for this study. In this case, the total water balance can be rewritten as:

$$P + SW_{in} + H_{in} - \Delta S/\Delta t = ET + SW_{out} + H_{out} \qquad (2)$$

The net basin flux (NetFlux), which may be directly available for human use can be derived by rearranging the Eq. (2).

$$\begin{aligned} NetFlux &= (P - ET) + SW_{in} + H_{in} - \Delta S/\Delta t \\ &= SW_{out} + H_{out} \end{aligned} \qquad (3)$$

According to Eq. (3), two different forms can be used to obtain net flux depending on the data available. When the latter form of net flux is used, only two data sets, outflow of surface water and human water withdrawal, are required and those are typically available.

When considering water quality issues, the quantity that is hypothetically imported into the closed basin (W_{dilute}) to dilute the contaminated surface water should be added to the net flux. Thus, the latter form of Eq. (3) is rewritten as:

$$NetFlux = SW_{out} + H_{out} + W_{dilute} \qquad (4)$$

All terms in the water balance are normalized by dividing each term by the net system flux, which yields normalized human inflow (h_{in}) and outflow (h_{out}). Eq. (3) is used for estimating h_{in} and h_{out} without considering the water quality issue, while Eq. (4) is used when water quality is considered.

$$h_{in} = H_{in}/NetFlux \qquad (5)$$

$$h_{out} = H_{out}/NetFlux \qquad (6)$$

Plotting h_{in} versus h_{out} [calculated by Eq. (5) and (6)] for each watershed yields the water use regime. The target for water use intensity is a one-to-one ratio of h_{in} to h_{out}, or the 45° line that is seen on the graphs shown in the Result section. This line represents a state in which imports = exports, although the water returned is not necessarily of the same quality as the water withdrawn. In the water regime plots, the region below the 1:1 diagonal line represents the "withdrawal regime" (i.e., withdrawals > imports), and the region below the diagonal represents the "import regime" (imports > withdrawals). Unsustainable freshwater withdrawals may arise either from large withdrawals or significant water quality impairment or both.

The derivation of the freshwater-use regime is useful for analyzing the intra-seasonal and geographic differences within and among watersheds. However, the water-use regimes demonstrate the degree of human influence on a region's hydrology and not necessarily the water stress that results from such a condition. An objective measure must be derived to assess the relative water stress implied by a given watershed's water use regime. The criticality ratio – defined by Alcamo et al. (2000) as the ratio of water use to water availability – is used as a method of determining water stress. The levels of water stress are defined below:

- 0 – 0.1: no stress
- 0.1 – 0.2: low stress
- 0.2 – 0.4: mid stress
- 0.4 – 0.8: high stress
- 0.8 – 1: very high stress

These criticality ratios can be directly applied to the water use regime. In the modified water use regime described above,

$$h_{out} = \frac{H_{out}}{NetFlux} \tag{7}$$

The criticality ratio is defined as:

$$\frac{water\ use}{water\ availability} = \frac{H_{out}}{(P - ET) + SW_{in} + H_{in} - \Delta S/\Delta t} = \frac{H_{out}}{NetFlux} = h_{out} \tag{8}$$

The above levels of water stressed defined by the criticality ratio can easily be included in the water use regime.

After deriving the water-use regime for each watershed, a worst-case scenario was examined to explore issues that may result in the inappropriateness of a certain location for ethanol production. Returning to the USGS stream flow measurement data, the discharge rate at the lower fifth percentile of all years was used in place of the mean discharge rate to re-calculate the water use regime. This reveals the main problem inherent with drought years: a much greater amount of water input is required to dilute harmful chemicals to acceptable levels. The water-use regimes were re-calculated using the twenty-fifth percentile of discharge data to demonstrate the effects of less extreme drought years.

Indiana Watersheds Evaluated

The freshwater use regime is constructed for the HUC-8 watersheds in which bioethanol plants are in operation to compare how freshwater use by biofuels production impacts local hydrologic stress. As of December 2010, Indiana had 12 completed ethanol plants and one more under construction (Figure 1). The combined ethanol production of the plants completed and the additional one under construction will exceed 1.1 billion gallons per year, which represents 7% of the U.S. ethanol industry (ISDA 2010). The biorefineries are located close to each other, and therefore conflicts over water use are likely to occur. Corn-based ethanol production with the nameplate capacities of 150 to 415 million liters typically requires feedstocks to be supplied from regions that stretch several tens of miles of radius from a plant's location. While production process itself may induce local conflicts over freshwater use, the spatial range of impact caused by feedstock production can be expanded far beyond the scale of county and even of a watershed. Thus, among the Indiana biorefineries, nine located in eight watersheds within a similar hydro-geologic region were selected (Table 1).

Table 1. Selected watersheds for the construction of water use regime.

Watershed	Total Area (km^2)	Crop (Corn) Area (km^2)	Biorefinery	Production Capacity (MG/year)
(A) Iroquois	2,208	902	Iroquois Bio-energy	40
(B) Eel (Upper)	2,112	1,313	POET Biorefining – North Manchester	65
(C) Middle Wabash Deer	1,731	1,259	The Andersons	110
(D) Upper Wabash	4,229	922	Indiana Bio-Energy	110
(E) Mississinewa	2,114	577	Central Indiana Cardinal Energy	40 100
(F) Salamonie	1,450	1,037	POET Biorefining - Portland	65
(G) Upper White	7,044	1,506	POET Biorefining - Alexandria	60
(H) Middle Wabash – Little Vermillion	5,887	3,480	Valero Energy	100

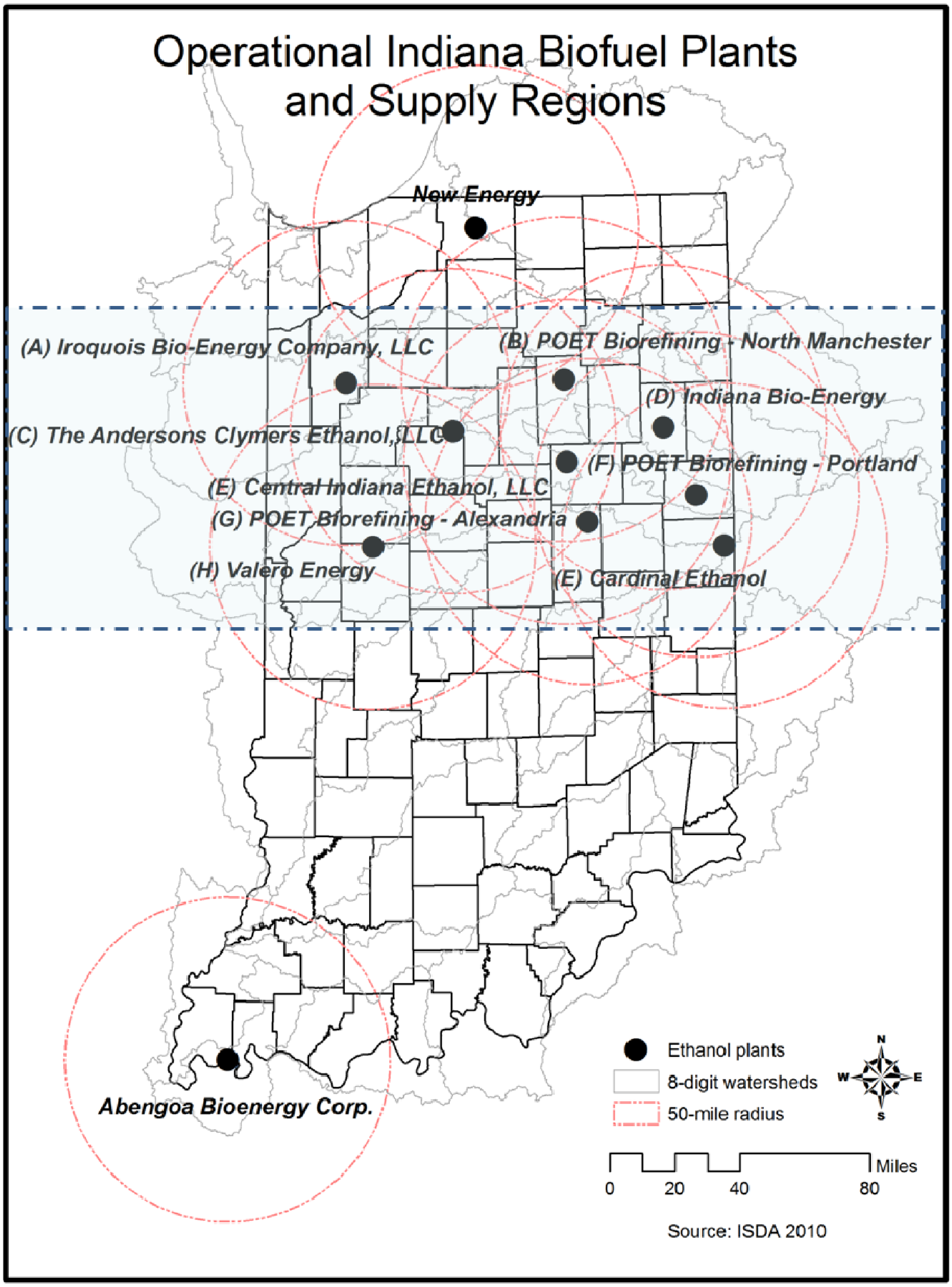

Figure 1. Corn-based ethanol plants in Indiana and the site selection for water use regime construction based on their relative distances. Blue highlighted area represents the geographic area within which the hydrogeologic characteristics are expected to be similar.

Primary Findings

Water-use regime plots were generated for all of the watersheds evaluated, and will be included in a research publication that is being currently prepared. Here, we present some representative plots for the Salamonie watershed (Figure 2) to illustrate the water-use regimes, and summarize the primary findings based on similar analyses in all other watersheds.

1. Given the humid climate and because crop irrigation is not a dominant demand, water regime plots at the *watershed scale* suggest minimum freshwater stress at the annual or even monthly time scales under *average* weather conditions. That is, consumptive uses of freshwater withdrawals by major sectors (utilities and industries) are small (even the maximum h_{out} is less than 0.1, which means no stress according to criticality ratio). Note that the data points lie on or close to the 1:1 line (withdrawals ~ return flows).
2. This evaluation, however, changes dramatically when *water-quality impairment* is accounted for in construction of the water-use regime plots; all watersheds we evaluated would be judged to be under severe water stress. Here, we considered water quality impairment from non-point sources. Stream concentrations of the herbicide atrazine exported from watersheds (based on % area planted to corn) was used to represent surface water quality impairment.
3. We have assumed that pollutant discharges from point sources (e.g., industrial operations, including biorefineries) meet all regulatory standards such that water quality is above acceptable thresholds for human and ecological health. However, further research is needed to establish that our assumption is indeed valid.
4. Under *drought conditions*, all watersheds we examined would be judged as being under severe stress both from quantity and quality perspectives. In case of Salamonie watershed, the water stress in summer season increased beyond 0.2 (mid-stress) and reached 0.45 (high-stress) in August.
5. Competing demands for freshwater are most likely to be experienced at spatial scales smaller than a watershed scale. That is, at a township or community level, freshwater demands from multiple sectors would be a significant issue as new demands from biorefineries are added. This is especially important since freshwater withdrawals are from groundwater sources, but return flows are to surface waters (streams). Thus, continued depletion by increasing pumping from aquifers can, over time, result in significant water stress at the local level.
6. Freshwater use data we utilized in our analysis came from USGS reports which are published once every five years and are available aggregated only at the county level. We did not access data that might be available with the local authorities who issue permits for groundwater use. Our assessments would be enhanced if such local-scale data were used to generate the water regime plots, and these plots would be even more useful to local water managers.
7. With likely changes in rainfall patterns [e.g., increasing probability of intense extreme events of floods and droughts], increasing competition for freshwater resources is expected. As such, careful assessment of shifting water-use regimes [increased stress] is needed in water allocation decisions.

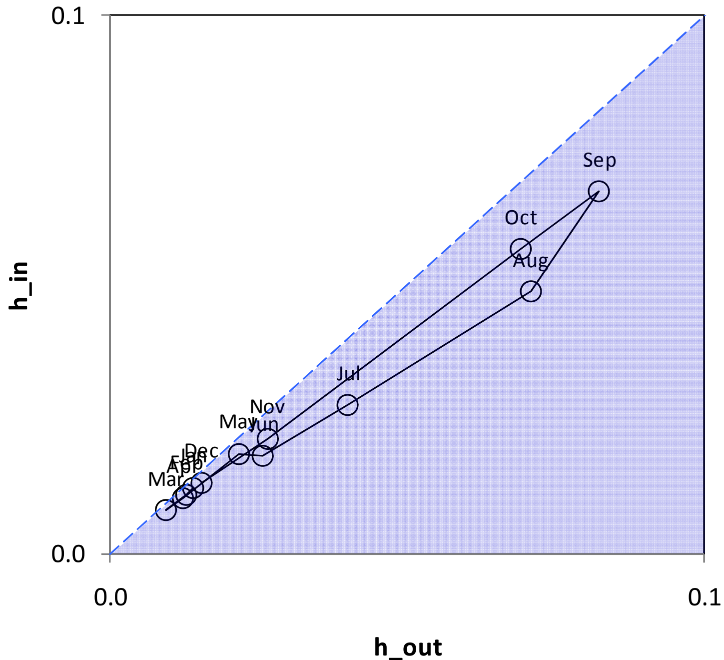

Figure 2A. Monthly variation of water use regime in mean weather condition <u>without the consideration of water quality.</u>

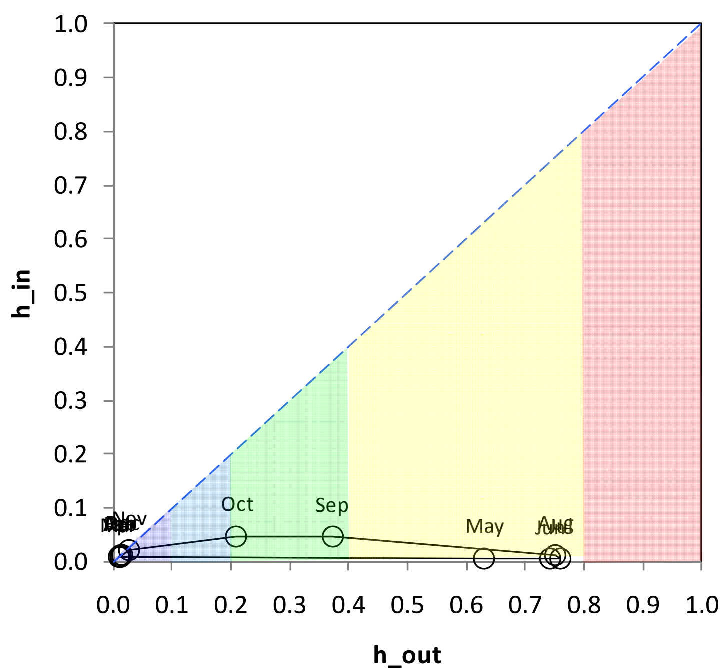

Figure 2B. Monthly variation of water use regime in mean weather condition <u>with the consideration of water quality</u>

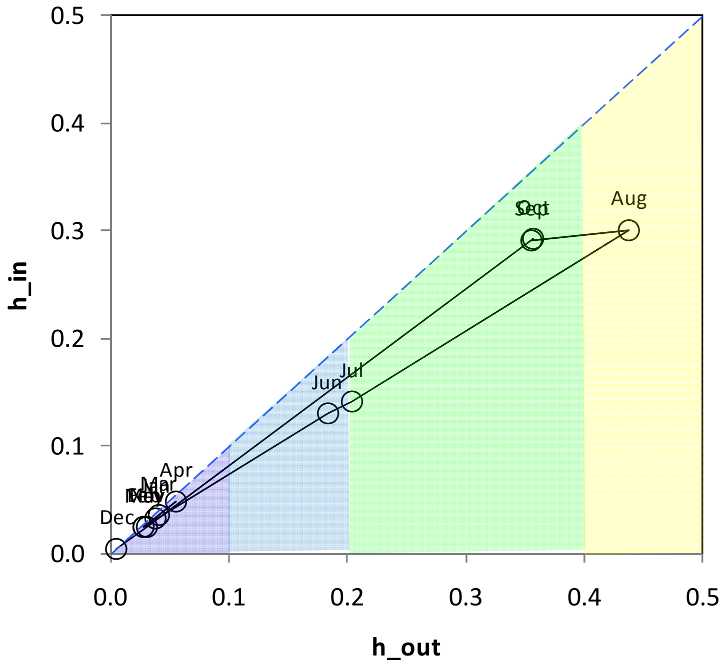

Figure 2C. Monthly variation of water use regime under extreme drought condition without the consideration of water quality

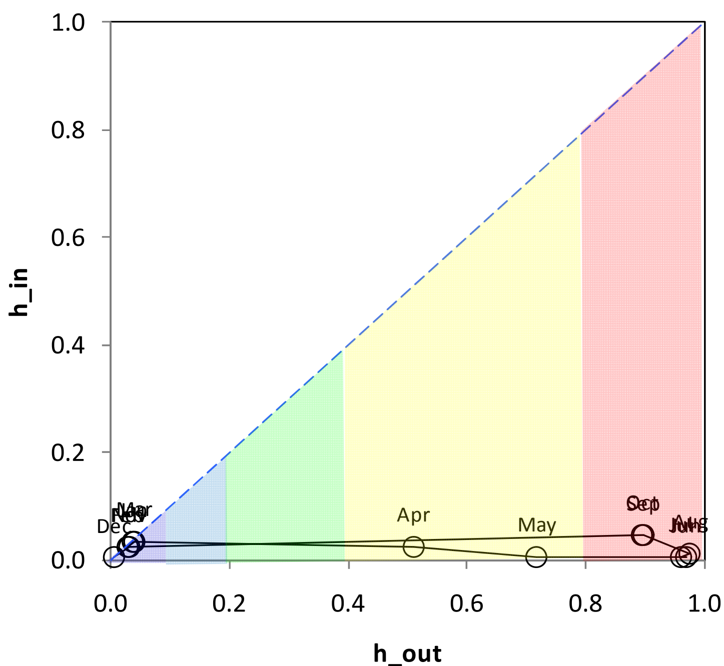

Figure 2D. Monthly variation of water use regime under extreme drought condition with the consideration of water quality

Practical Implications

Current water-use status of biofuel refineries located in several watersheds within central Indiana was evaluated. Our results will provide an assessment tool as well as critical information to local governments and water management authorities to: (1) assist successful decision making on selecting which biomass conversion technology should be adopted, (2) where to locate these technologies in terms of minimizing local and regional impact on fresh water resources; and (3) plan sustainable expansion of biofuel production to reach overarching goals of energy independence.

Graduate Student training

This project was lead by Mr. Jeryang Park (CE PhD), mentored by Professor Suresh Rao (CE). Mr. Parks' PhD dissertation topic focuses on modeling resilience of biofuel production systems, and the dynamics of coupled industrial systems (biorefineries) and natural systems (biomass production; water resources). His research will examine adaptive strategies needed to promote sustainability of biofuel production under volatile (i.e., stochastic forcing & feedbacks) of climate and markets. Mr. Park assisted Professor Rao in teaching the Global Water Resources Sustainability (CE597), a graduate course taught during spring 2010 semester. This inter-disciplinary course had an enrollment of about 15 graduate students, derived from engineering, agriculture, and liberal arts programs. The class included several students from the Ecological Science and Engineering Inter-disciplinary Graduate Program (ESE-IGP). Initial parts of this study (e.g., data gathering; conceptual model development, etc) were conducted as a class project within this CE597 course. Mr. Park led a group of the following students to compile the data, and develop the preliminary assessment: Carson Reeling (M.S. student; Agricultural Economics Department); Elizabeth Cox (M.S. student; ESE-IGP); Ryan Hultgren (senior; Civil Engineering), Kasey Faust (M.S. student; Civil Engineering). Mr. Reeling played a key role throughout the project period in working with Mr. Park and Dr. Rao to compile the data, complete the data analyses, and generate the final report.

Graduate Student Evaluation [Carson Reeling]

In the spring of 2010, I enrolled in Dr. Rao's class, "Water Resources and Sustainability." My training is in agricultural economics, but having been born and raised in the high desert of Eastern California, I am particularly interested in water resource management. I was therefore very happy to find a class in water resource management that, despite being taught in the civil engineering department, was highly accessible to students of different backgrounds.

A requirement of the class was to develop a term project that explored some component of water resource sustainability. Dr. Rao and his graduate student, Jeryang Park, presented me and other classmates with the opportunity to satisfy this requirement by contributing to the research project supported by your grant. I believed that the project had the potential to be both challenging and successful, so I chose to participate.

Having worked on the project over the course of spring semester, my initial assessment proved to be correct. The project challenged me to expand my academic horizon beyond economics and into the physical sciences. While previously only economic considerations seemed relevant, analyzing the basic hydrology behind biofuel plant location decisions and the effects of agricultural production on water quality taught me the value of expanding my perspective to take a more systems-oriented approach to researching environmental issues.

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